Inflation, SUSY breaking, and cosmological attractors

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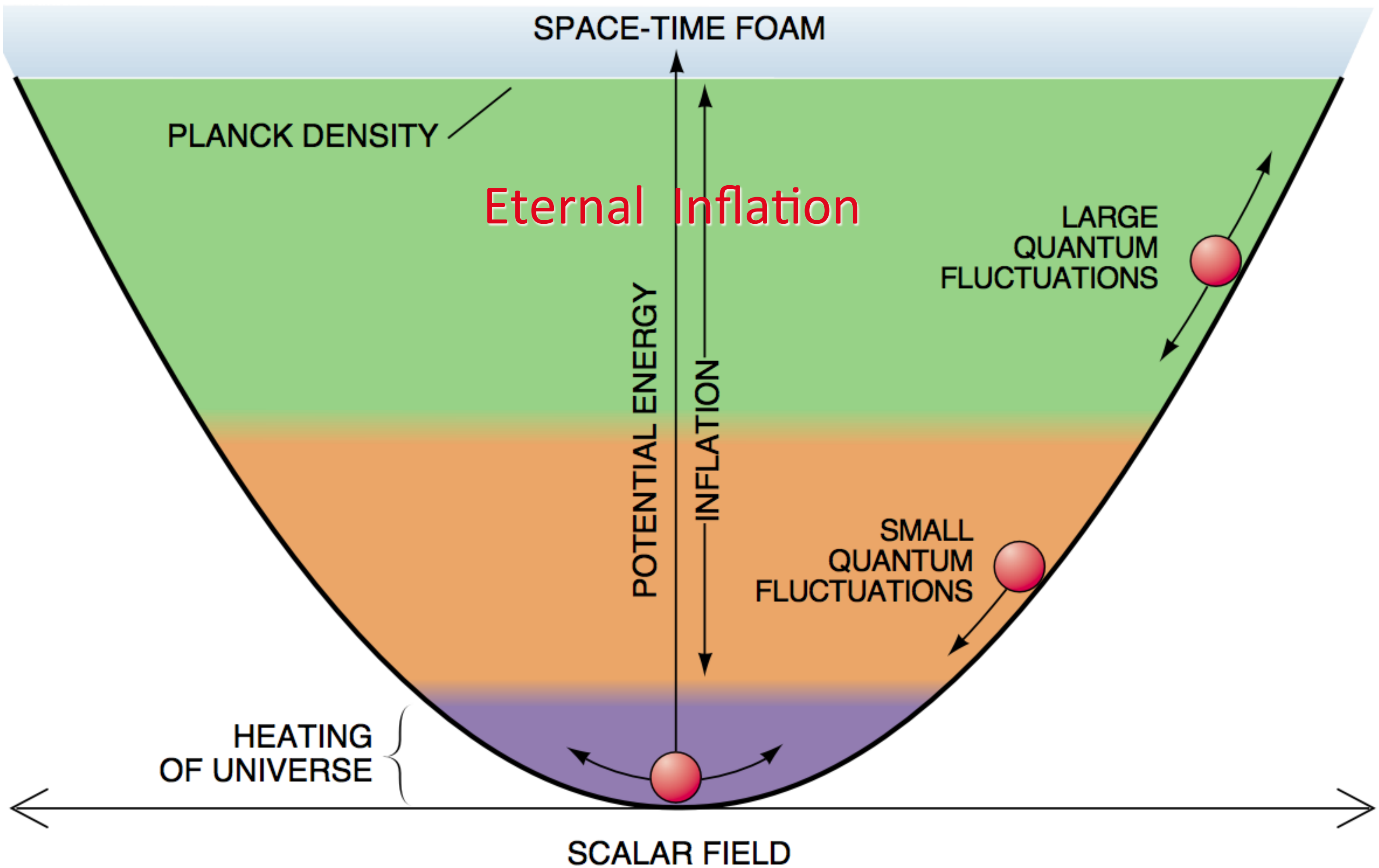
with Kallosh, Carrasco, Ferrara, Roest, Galante, Scalisi

Our goal is to find simple inflationary models which fit the data and can be implemented in string theory or supergravity

In addition to describing inflation, we would like also to describe dark energy and SUSY breaking

The simplest chaotic inflation model

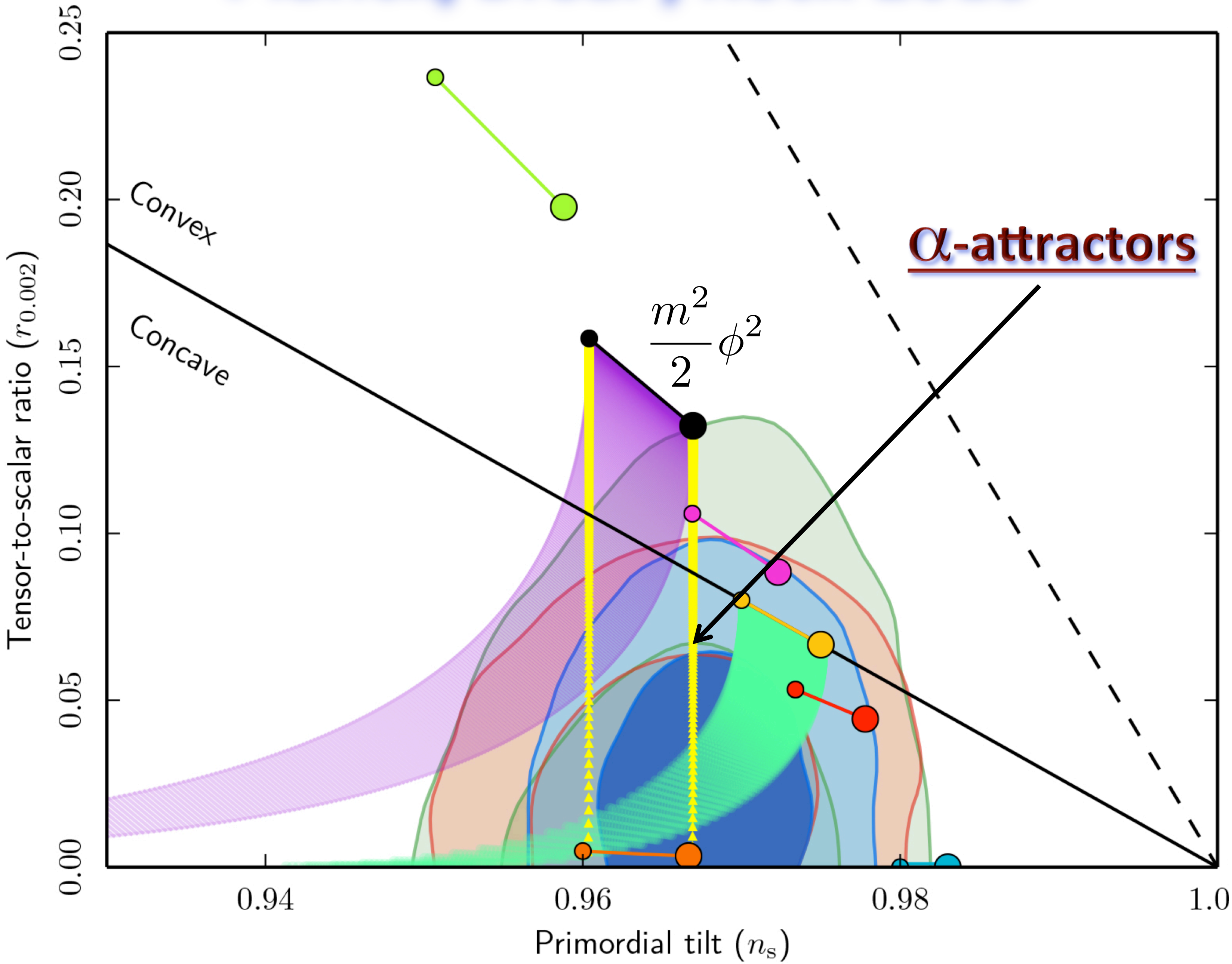
$$V(\phi) = \frac{m^2}{2}\phi^2$$



Planck data suggest that this simplest chaotic inflation model should be modified.

The two vertical yellow lines in the next slide will show the results of a minor modification of this model versus the results of Planck 2015.

Planck/BICEP/Keck 2015



What is the meaning of α-attractors?

Start with the simplest chaotic inflation model

$$\frac{1}{\sqrt{-g}}\mathcal{L} = \frac{1}{2}R - \frac{1}{2}\partial\phi^2 - \frac{1}{2}m^2\phi^2$$

Modify its kinetic term

$$\frac{1}{\sqrt{-g}}\mathcal{L} = \frac{1}{2}R - \frac{1}{2}\frac{\partial\phi^2}{(1-\underline{\frac{\phi^2}{6\alpha}})^2} - \frac{1}{2}m^2\phi^2$$

Switch to canonical variables $\phi = \sqrt{6\alpha}\,\tanh\frac{\varphi}{\sqrt{6\alpha}}$

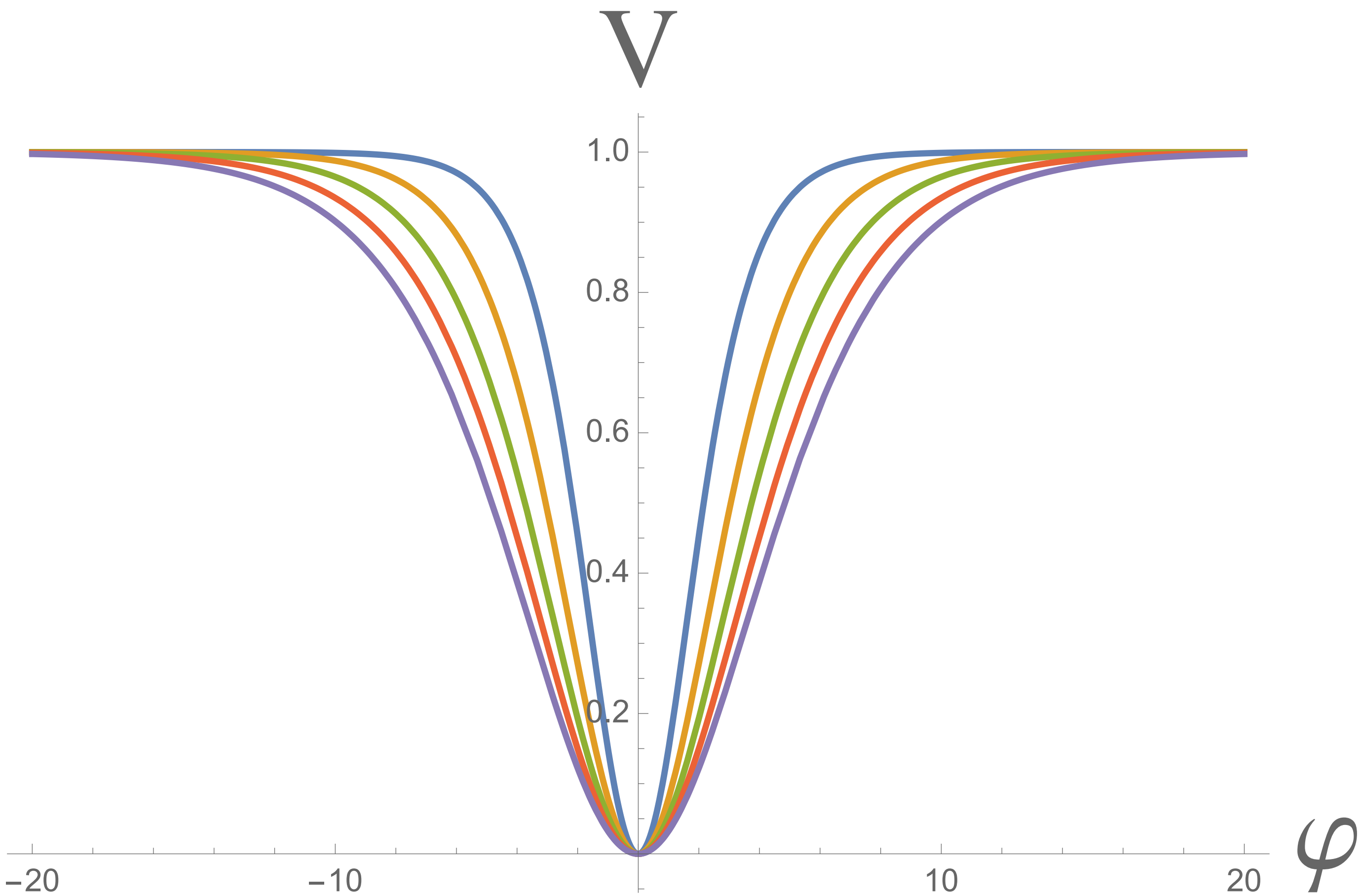
The potential becomes

$$V = 3\alpha\, m^2 \tanh^2\frac{\varphi}{\sqrt{6\alpha}}$$

T-models

$$V = f(\tanh^2 \frac{\varphi}{\sqrt{6\alpha}})$$

$$n_s = 1 - \frac{2}{N}, \qquad r = \alpha \frac{12}{N^2}$$



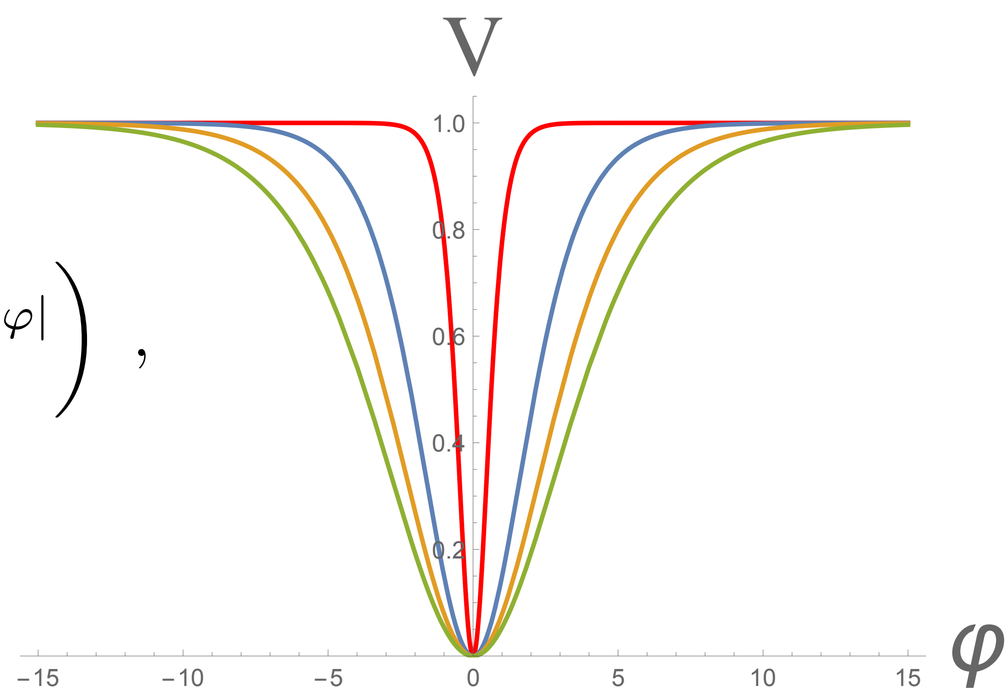
Similar model has been proposed 30 years ago by Goncharov and A.L. in JETP **59**, 930 (1984). It was the first paper on chaotic inflation in supergravity, but it was nearly forgotten. It corresponds to $\alpha = 1/9$

$$n_s = 1 - \frac{2}{N} \approx 0.967, \qquad r \sim 4 \times 10^{-4}$$

Red line – GL model 1984

$$V(\varphi) = \frac{\mu^2}{9}\left(1 - \frac{8}{3}\, e^{-\sqrt{6}|\varphi|}\right) ,$$

for $\varphi \gtrsim 1$

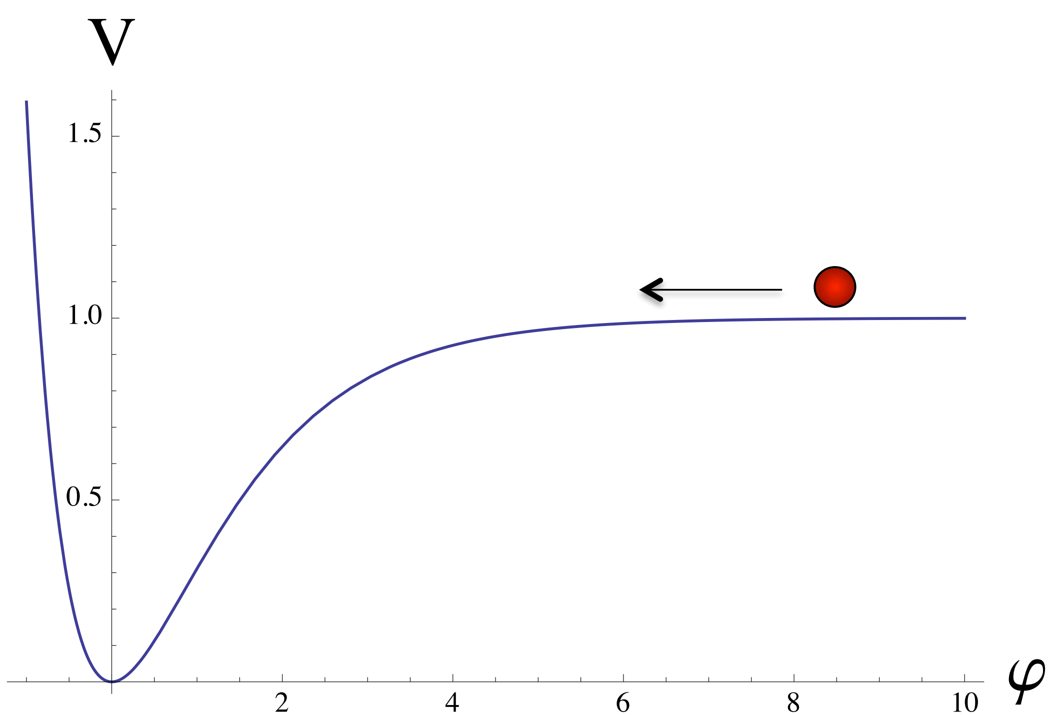


Starobinsky model

$$L = \sqrt{-g}\left(\frac{1}{2}R + \frac{R^2}{12M^2}\right)$$

$$\tilde{g}_{\mu\nu} = (1 + \phi/3M^2)g_{\mu\nu} \qquad \varphi = \sqrt{\tfrac{3}{2}}\ln\left(1 + \tfrac{\phi}{3M^2}\right)$$

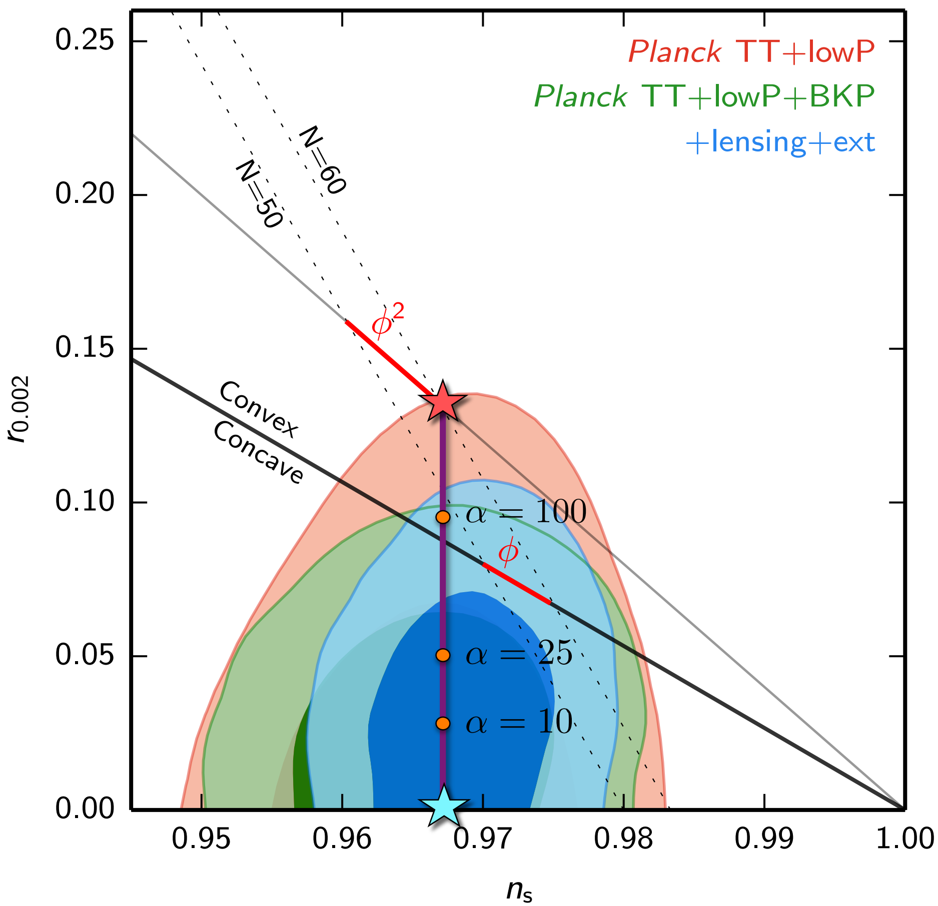
$$L = \sqrt{-\tilde{g}}\left[\frac{1}{2}\tilde{R} - \frac{1}{2}\partial_\mu\varphi\partial^\mu\varphi - \frac{3}{4}M^2\left(1 - e^{-\sqrt{2/3}\,\varphi}\right)^2\right]$$

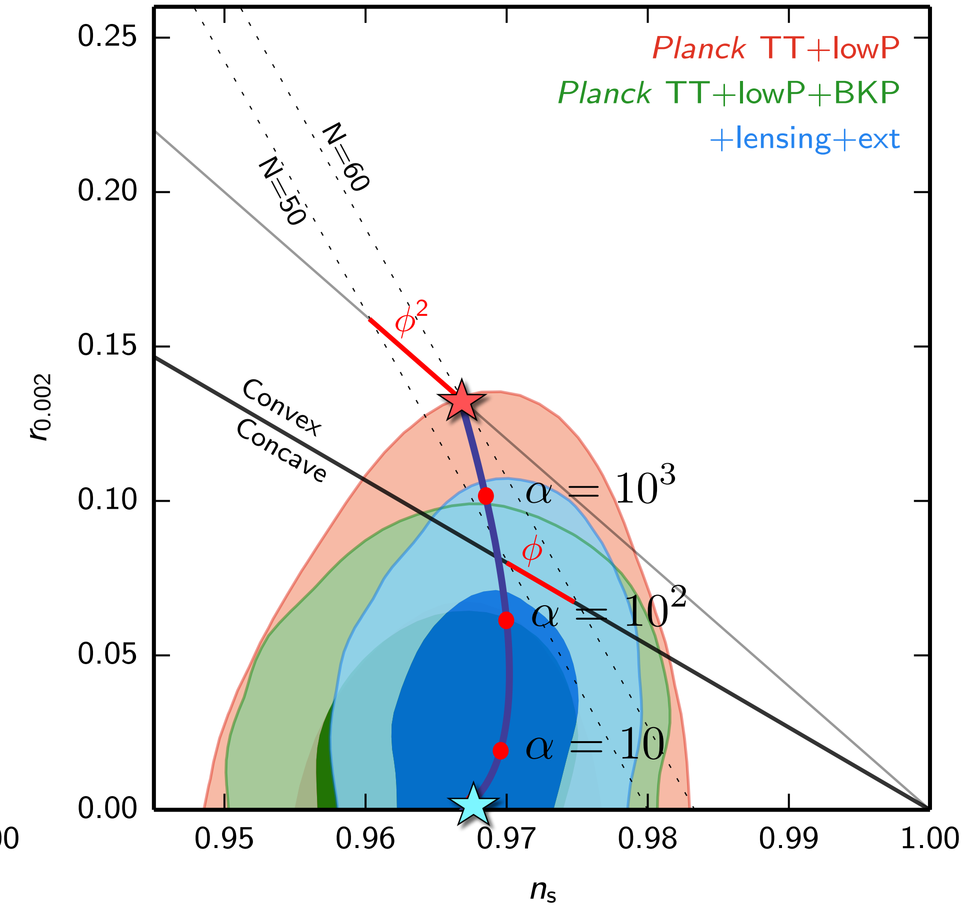


Whitt 1984

Identified with the Starobinsky model only in 1988:

Barrow 1988
Maeda 1988
Coule, Mijic 1988





$$\frac{1}{2}R - \frac{1}{2}\frac{\partial\phi^2}{(1-\frac{\phi^2}{6\alpha})^2} - \frac{1}{2}m^2\phi^2$$

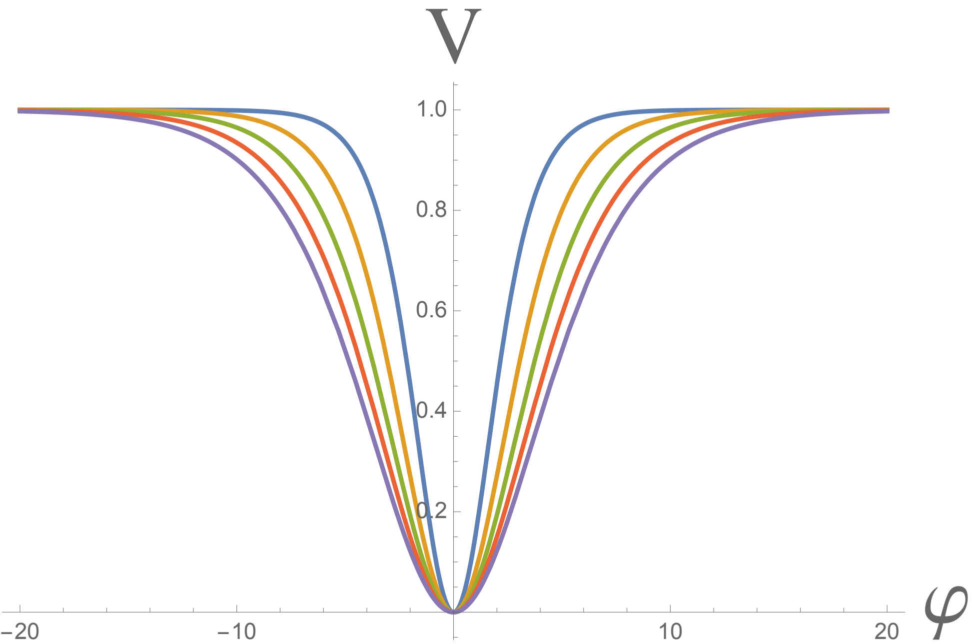
$$\frac{1}{2}R - \frac{1}{2}\frac{\partial\phi^2}{(1-\frac{\phi^2}{6\alpha})^2} - \frac{1}{2}m^2\frac{\phi^2}{(1+\frac{\phi}{\sqrt{6\alpha}})^2}$$

Simplest T-models

Simplest E-models

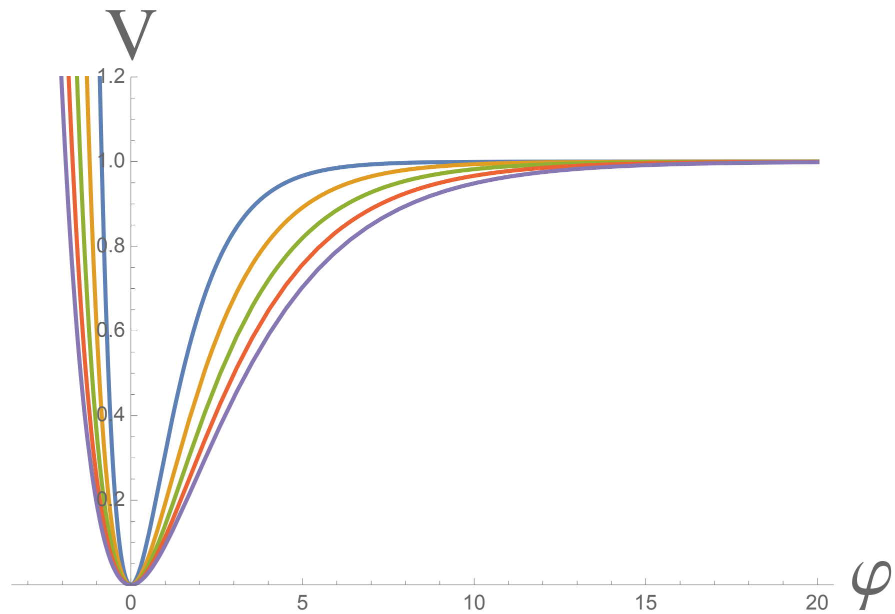
Ferrara, Kallosh, AL, Porrati, 2013, Kallosh, AL, Roest 2013

Simplest T-models



$$\frac{1}{2}R - \frac{1}{2}\partial\varphi^2 \;\; - \alpha\mu^2\Big(\tanh\frac{\varphi}{\sqrt{6\alpha}}\Big)^2$$

Simplest E-models



$$\frac{1}{2}R - \frac{1}{2}\partial\varphi^2 \;\; - \alpha\mu^2\Big(1 - e^{\sqrt{\frac{2}{3\alpha}}\varphi}\Big)^2$$

Coincides with the Starobinsky model for $\alpha = 1$.

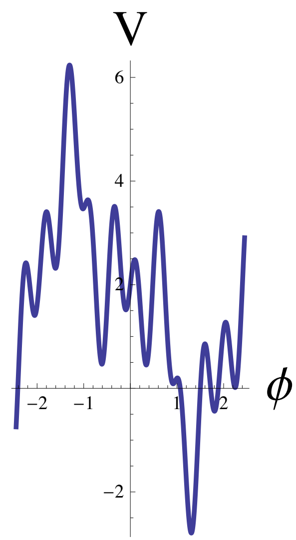
Why all of these different models have similar cosmological predictions for small α?

Stretching and flattening of the potential is similar to stretching of inhomogeneities during inflation

Kallosh, AL 2013

Potential in the **original variables** with kinetic term

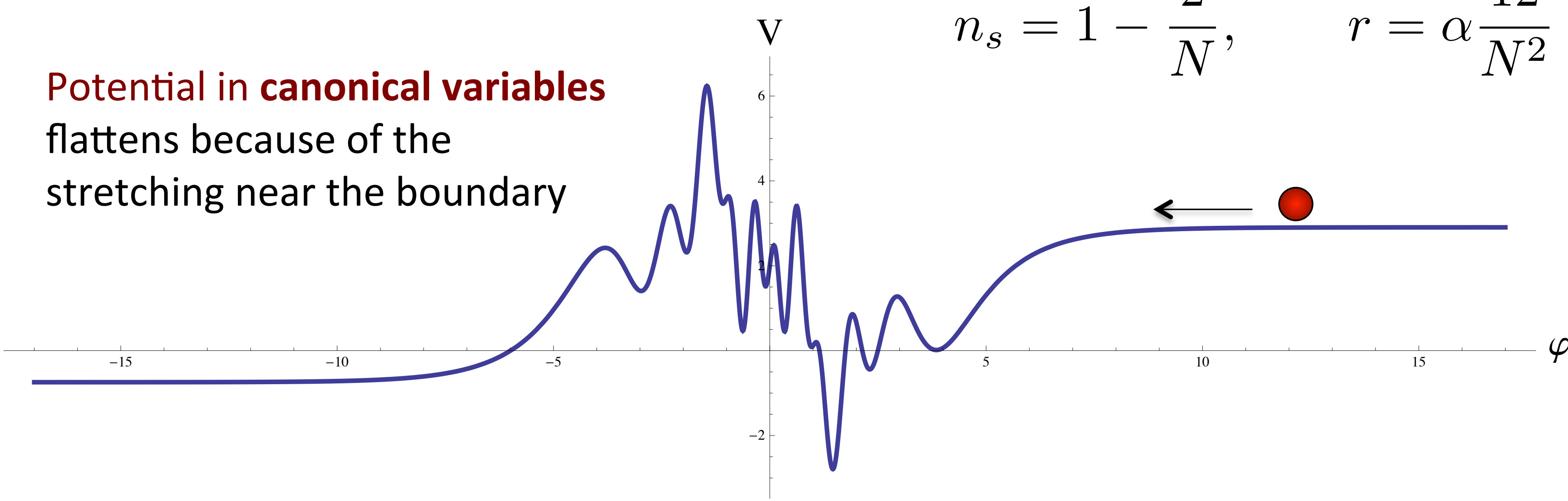
$$\frac{1}{2}\,\frac{\partial\phi^2}{(1-\frac{\phi^2}{6\alpha})^2}$$



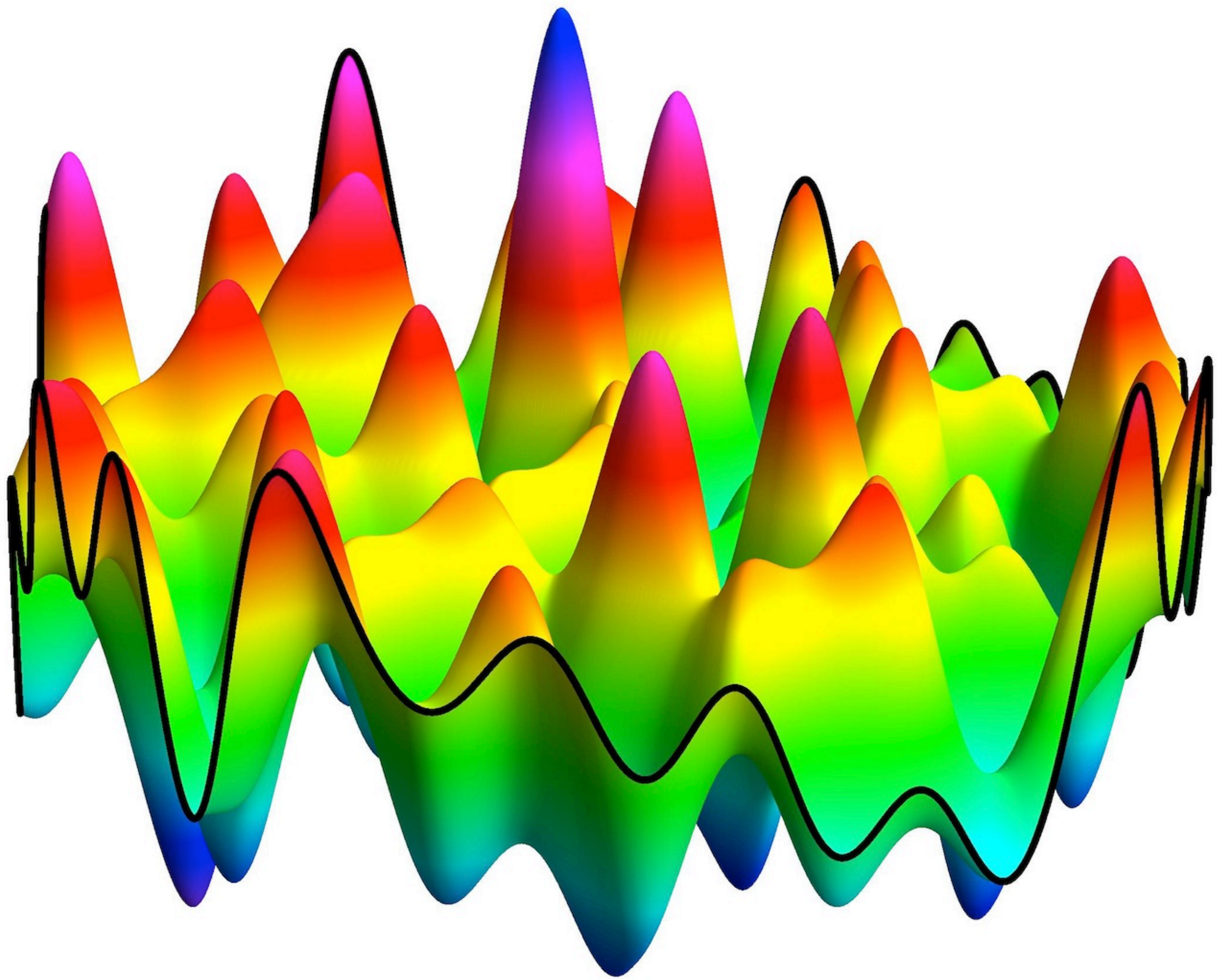
All of these models predict

$$n_s = 1-\frac{2}{N}, \qquad r = \alpha\frac{12}{N^2}$$

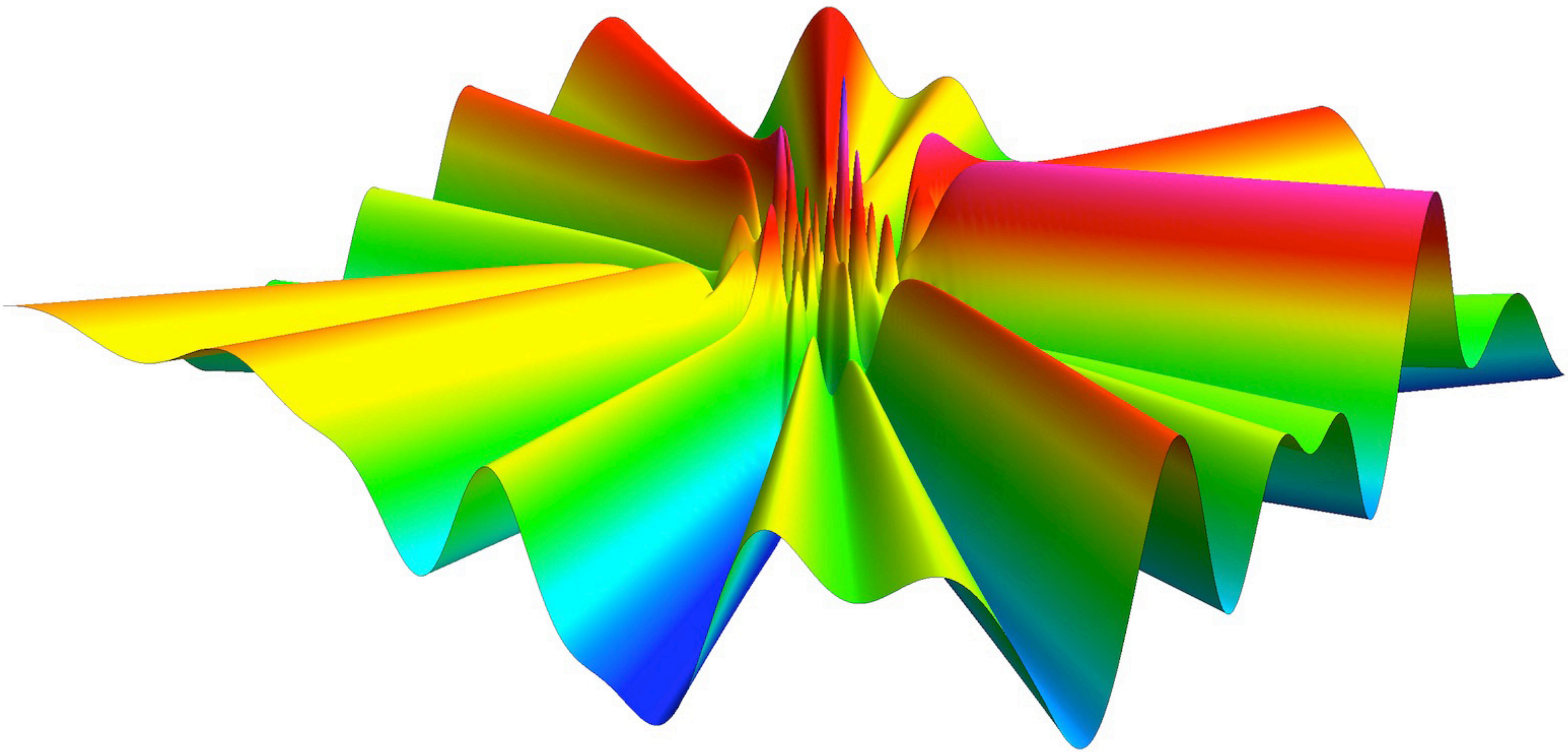
Potential in **canonical variables** flattens because of the stretching near the boundary



More general potentials in terms of the original conformal variables. Naively, one would not expect inflation in theories with random supergravity potentials:



Stretching upon converting to canonical variables in the Einstein frame leads to inflation along dS valleys, and universality of inflationary predictions, just as in the single-field models



The essence of α-attractors

Galante, Kallosh, AL, Roest 1412.3797

$$\frac{1}{2}R - \frac{3}{4}\alpha\left(\frac{\partial t}{t}\right)^2 - V(t)$$

Suppose inflation takes place near the pole at t = 0, and

$V(0) > 0 \qquad V'(0) < 0,$ and V has a minimum nearby

Then in canonical variables

$$\frac{1}{2}R - \frac{1}{2}(\partial\varphi)^2 - V_0(1 - e^{-\sqrt{\frac{2}{3\alpha}}\varphi} + \ldots)$$

and, in the leading approximation in 1/N, **almost independently on V(t)**

$$n_s = 1 - \frac{2}{N}, \qquad r = \alpha\frac{12}{N^2}$$

The essence of α-attractors

Galante, Kallosh, AL, Roest 1412.3797

THE BASIC RULE:

For a broad class of cosmological attractors, the spectral index n_s depends mostly on the order of the pole in the kinetic term, while the tensor-to-scalar ratio **r** depends on the residue. Choice of the potential almost does not matter, as long as it is non-singular at the pole of the kinetic term. Geometry of the moduli space, not the potential, determines much of the answer.

THE REMAINING PROBLEM:

Can we get a pole in the kinetic term from something more fundamental than a theory of a single scalar field, for example in supergravity?

Simplest example: T-model with $\alpha = 1$

$$K = -3\log(1 - Z\bar{Z}) + S\bar{S}, \qquad W = mSZ$$

There is a boundary of the moduli space at $|Z|^2=1$

The minimum of the potential is at Im Z = S = 0.

$$Z = \bar{Z} = \tanh\frac{\varphi}{\sqrt{6}}, \qquad S = 0$$

$$V = \tanh^2\frac{\varphi}{\sqrt{6}}$$

α-attractors in supergravity

$$K = -3\alpha \log\left(1 - Z\bar{Z}\right) + S\bar{S}$$ Disk variables

$$T = \tfrac{1+Z}{1-Z}, \quad T^{-1} = \tfrac{1-Z}{1+Z}$$

$$K = -3\,\alpha\log\left(T + \bar{T}\right) + S\bar{S}$$ Half-plane variables

Alternatively, one can use $K = -3\alpha\log\left[1 - Z\bar{Z} - S\bar{S}\right]$

or

$$K = -3\log\left(1 - Z\bar{Z} + \frac{\alpha-1}{2}\frac{(Z-\bar{Z})^2}{1-Z\bar{Z}} - \frac{S\bar{S}}{3}\right)$$

We can stabilize S at 0, so in all final expressions after calculating V one can take S = 0.

As required for the cosmological attractors, moduli space has a boundary at T = 0 (or infinity), or, equivalently, at the disk boundary $|Z|^2=1$, for S = 0.

These models with S = 0 describe a broad class of cosmological attractors with universal cosmological predictions and a supersymmetric vacuum with V = 0.

If we want to make sure that S = 0 generically, and describe potentials with a minimum with SUSY breaking and non-vanishing V (cosmological constant), a novel ingredient helps a lot:

Nilpotent chiral superfields

Supersymmetry is there, but fermions may not have scalar partners.

Volkov, Akulov, 1972 Non-linearly realized supersymmetry: only fermions are present

Rocek, Lindstrom, 1978-1979, Komargodski, Seiberg 2009: nilpotent superfields
Antoniadis, Dudas, Ferrara and Sagnotti, 2014

Ferrara, Kallosh, AL, 2014 application to cosmology, generic superconformal case

Nilpotent superfields: the main rule for cosmology

Calculate potentials as functions of all superfields as usual, and then **DECLARE that S =0 for the scalar part of the nilpotent superfield**. No need to stabilize and study evolution of the S field.

Nilpotent Superfields and String Theory

Supersymmetric KKLT uplift

Based on kappa-symmetric D-branes

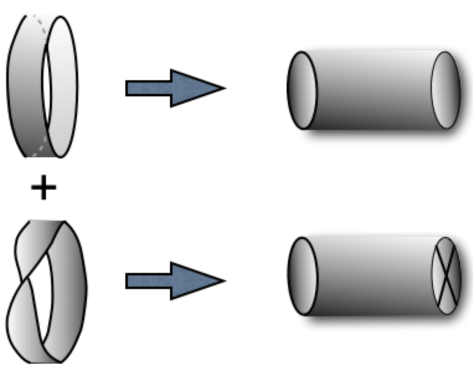
$\overline{\mathrm{D3}}$ and dS

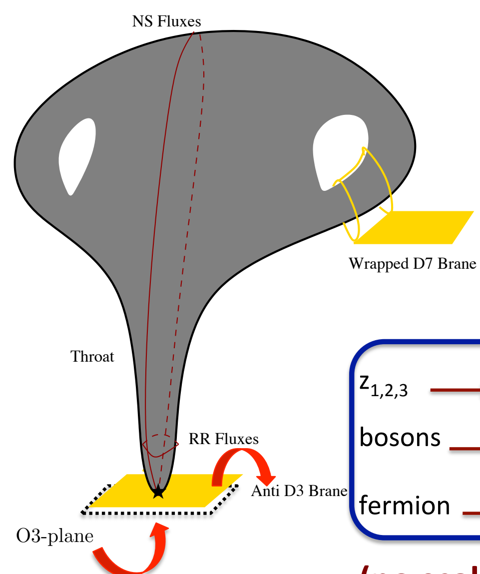
Bergshoeff, Dasgupta, Kallosh, Wrase, Van Proeyen 2015

String Theory Realizations of the Nilpotent Goldstino

Kallosh, Quevedo, Uranga 2015

Anti D3 Brane/O3⁻ Spectrum





$z_{1,2,3}$ →	$-z_{1,2,3}$
bosons →	-bosons
fermion →	fermion

Massless spectrum: Fermion=Goldstino

(no scalars, no gauge fields)

Refined description of α-attractors in SUGRA

Carrasco, Kallosh, AL, Roest

One can use an **equivalent** formulation, with Kahler potential preserving more of the symmetries of the theory.

Change the Kahler frame and use the most general W

$$K = -\frac{3}{2}\alpha \log\left[\frac{(1-Z\bar{Z})^2}{(1-Z^2)(1-\bar{Z}^2)}\right] + S\bar{S} \qquad W = A(Z) + SB(Z)$$

$$K = -\frac{3}{2}\,\alpha \log\left[\frac{(T+\bar{T})^2}{4T\bar{T}}\right] + S\bar{S} \qquad W = G(T) + SF(T)$$

New variables, Carrasco, Kallosh, AL

$$T = e^{\sqrt{\frac{2}{3\alpha}}\Phi}, \qquad Z = \tanh\frac{\Phi}{\sqrt{6\alpha}}$$

$$K = -3\alpha \log\left[\cosh\frac{\Phi-\bar{\Phi}}{\sqrt{6\alpha}}\right] + S\bar{S} \qquad W = g(\Phi) + Sf(\Phi)$$

Some simple but instructive examples

Pure de Sitter Supergravity

Ferrara, Kallosh, AL 2014: the action in the superconformal form

Bergshoeff, Freedman, Kallosh, Van Proeyen: a complete pure de Sitter supergravity INCLUDING FERMIONS

S is a nilpotent chiral superfield; no other fields

$$K = S\bar{S}, \qquad W = \sqrt{\Lambda}\, S$$

The theory describes **dS state** without scalar fields

$$V = \Lambda > 0$$

Next step: Poincare dS disk

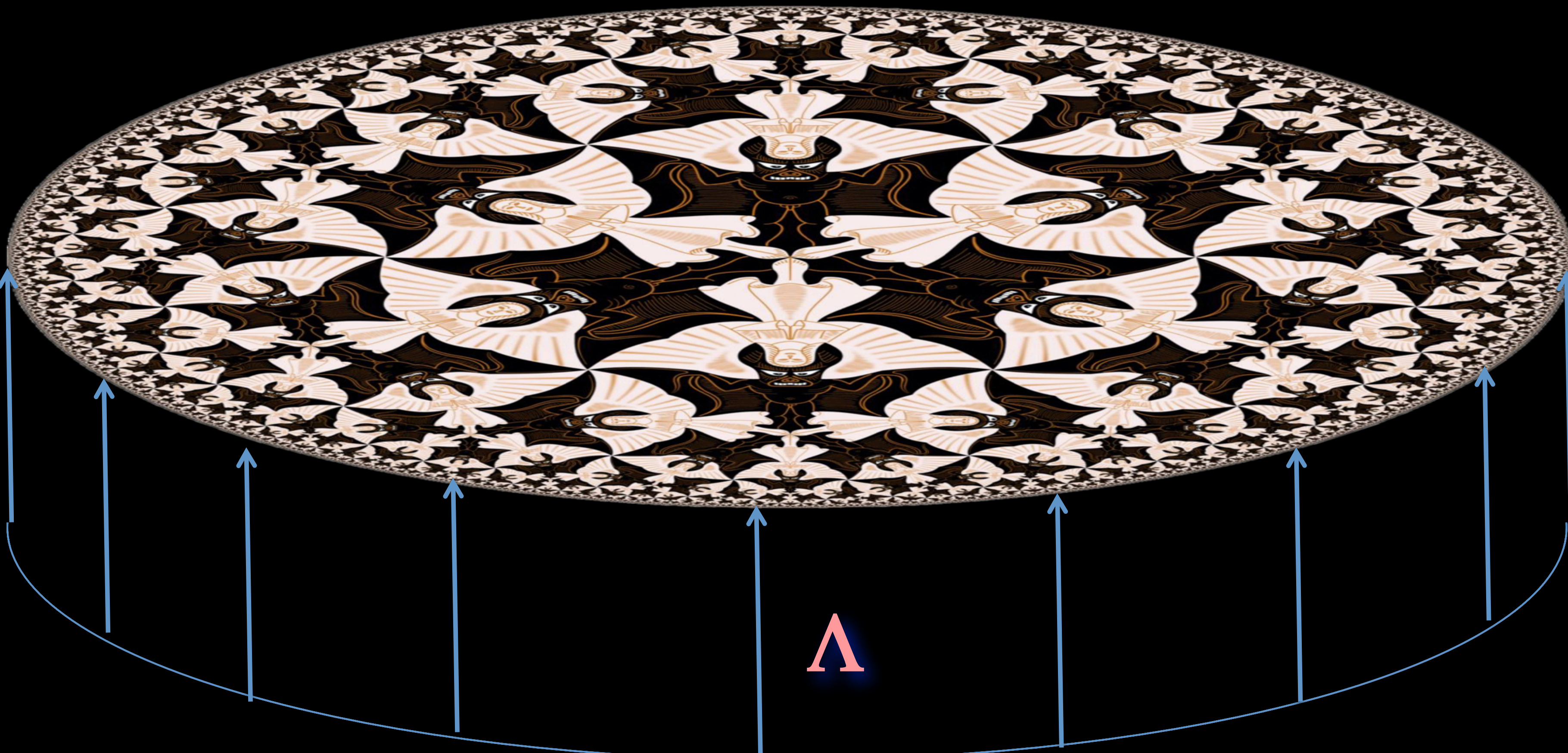
$$K = -\log\left[\frac{1 - Z\bar{Z} - S\bar{S}}{\sqrt{(1-Z^2)(1-\bar{Z}^2)}}\right] \qquad W = \sqrt{\Lambda}\, S$$

$$V = \Lambda$$

The scalar field Z is massless. It lives on the dS Poincare disk

$$|Z| < 1$$

This model describes the Poincare disk of radius R = 1 corresponding to dS universe with the cosmological constant Λ



α–attractors

$$K = -3\alpha \log \left[\frac{1 - Z\bar{Z} - S\bar{S}}{\sqrt{(1-Z^2)(1-\bar{Z}^2)}} \right]$$

Simplest T-model: $W = \sqrt{\alpha}\mu\, S\, Z$

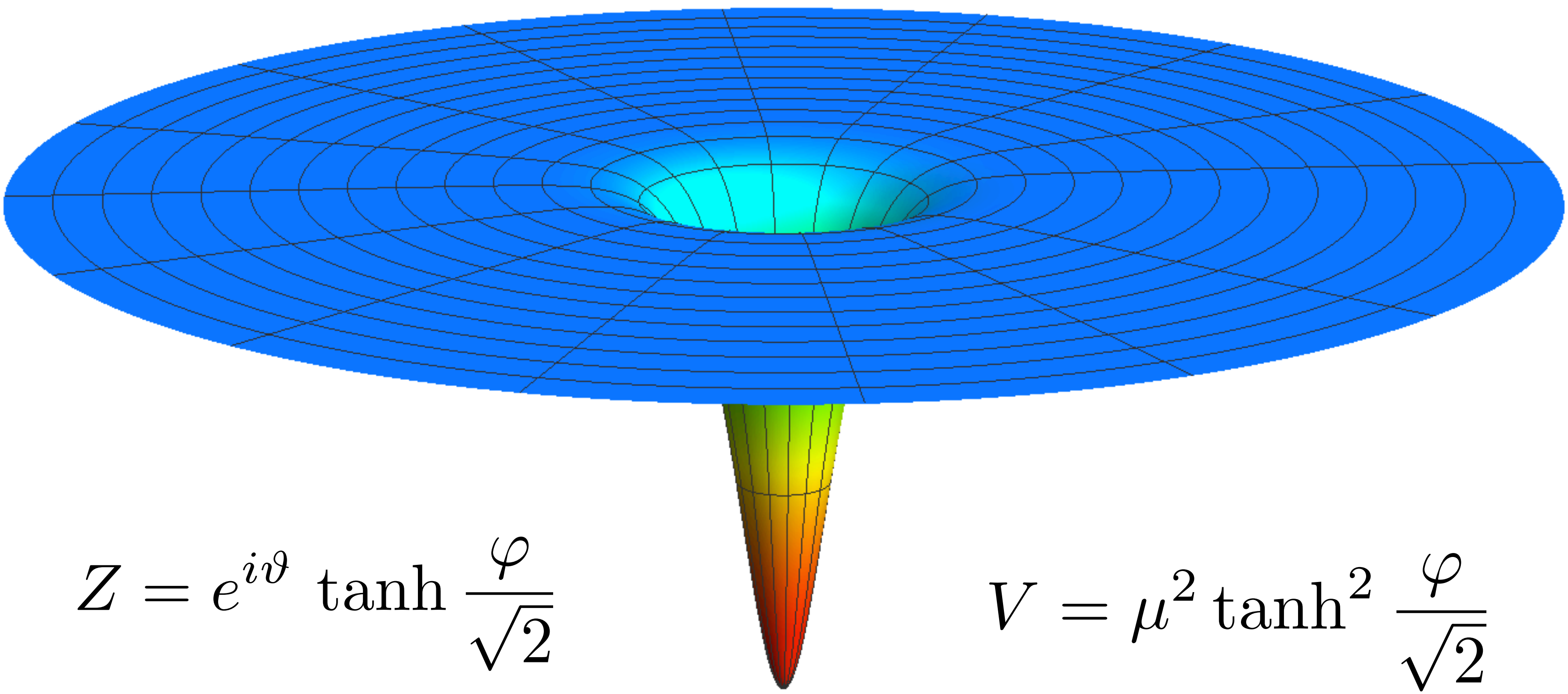
$$V \sim \alpha\, \mu^2 |Z|^2 = \alpha\, \mu^2 \tanh^2 \frac{\varphi}{\sqrt{6\alpha}}$$

Moduli space and Escher's Angels and Devils

This is the simplest quadratic inflationary potential, with angels and devils concentrated near the boundary of the moduli space

The same potential in terms of the canonical inflaton field for $\alpha = 1/3$

$$K = -\log\left[\frac{1 - Z\bar{Z} - S\bar{S}}{\sqrt{(1-Z^2)(1-\bar{Z}^2)}}\right] \qquad W = \mu\, S\, Z$$



$$Z = e^{i\vartheta}\ \tanh\frac{\varphi}{\sqrt{2}} \qquad V = \mu^2 \tanh^2\frac{\varphi}{\sqrt{2}}$$

Initial conditions for inflation

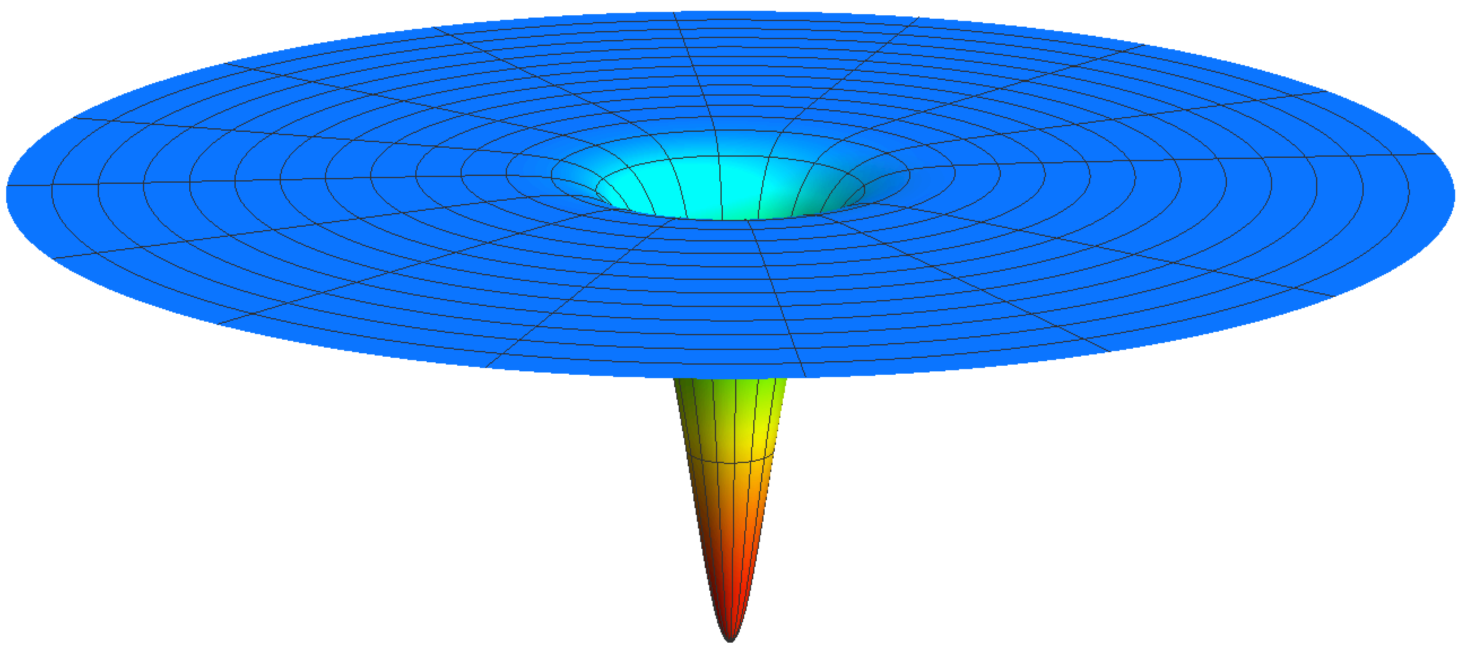
In the simplest chaotic inflation model $m^2\phi^2$, inflation begins at the Planck density under a trivial condition: the potential energy should be greater than the kinetic and gradient energy in a smallest possible domain of a Planckian size.

However, in a broad class of cosmological attractor models, inflation can begin only when the energy density drops from its Planck value by 10 orders of magnitude. Is it a problem?

Carrasco, Kallosh, AL   1506.0936

Potential defines infinite dS space, everywhere except a small vicinity of the minimum

The universe is born at the Planck density, 10 orders of magnitude above the dS disk. It may be very inhomogeneous, but if it expands, density of matter decreases. In 10^{-28} seconds it becomes dominated by dS energy density. After that, the field slowly rolls to the minimum. This solves the problem of initial conditions for inflation



Example: GL model of 1984 in modern formulation

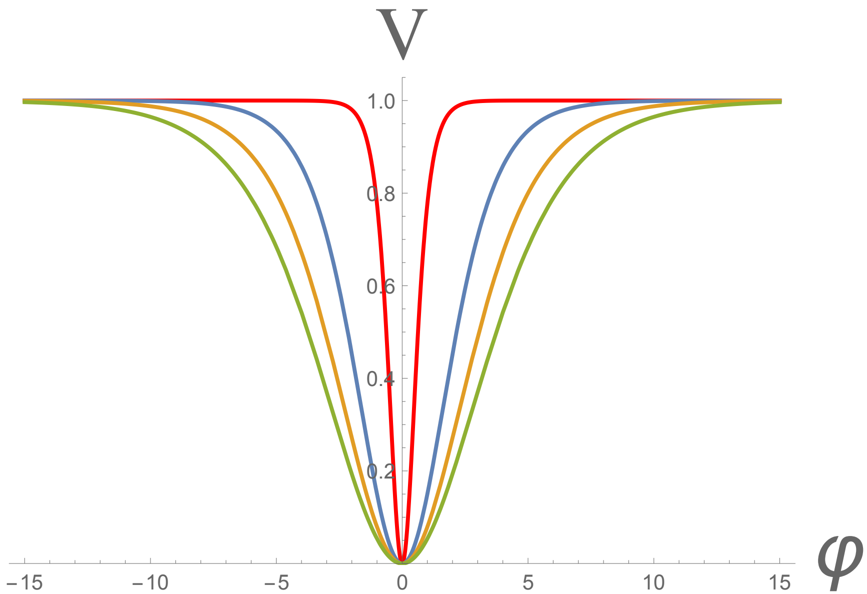
Goncharov, AL 1984
AL 2015

$$K = -\frac{1}{2}(\Phi - \bar{\Phi})^2$$

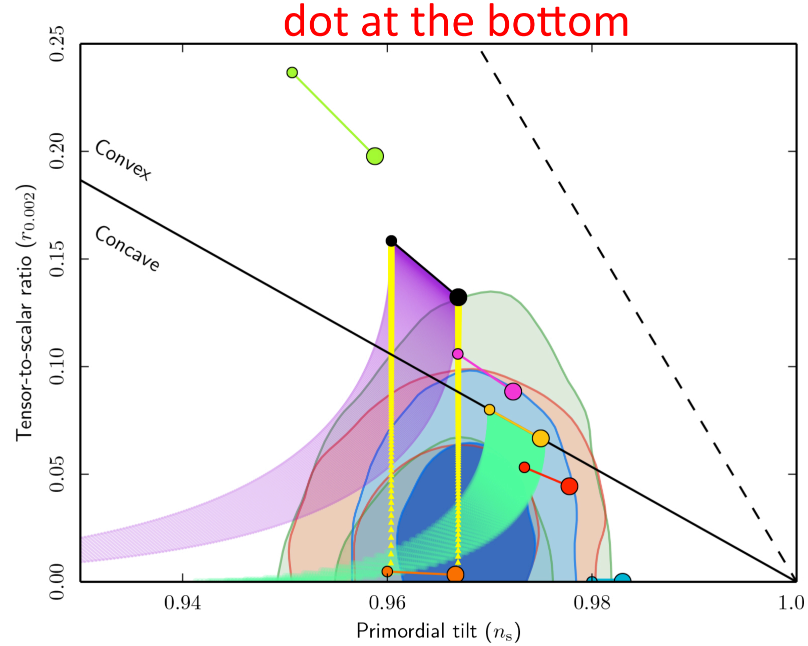
$$W = \frac{m}{6}\left(\cosh\sqrt{3}\Phi - \cosh^{-1}\sqrt{3}\Phi\right)$$

$$V(\phi) = \frac{m^2}{4}\left(1 - \frac{8}{3}\, e^{-\sqrt{6}|\phi|}\right)$$

GL potential is shown by red line



Prediction is shown by the orange dot at the bottom



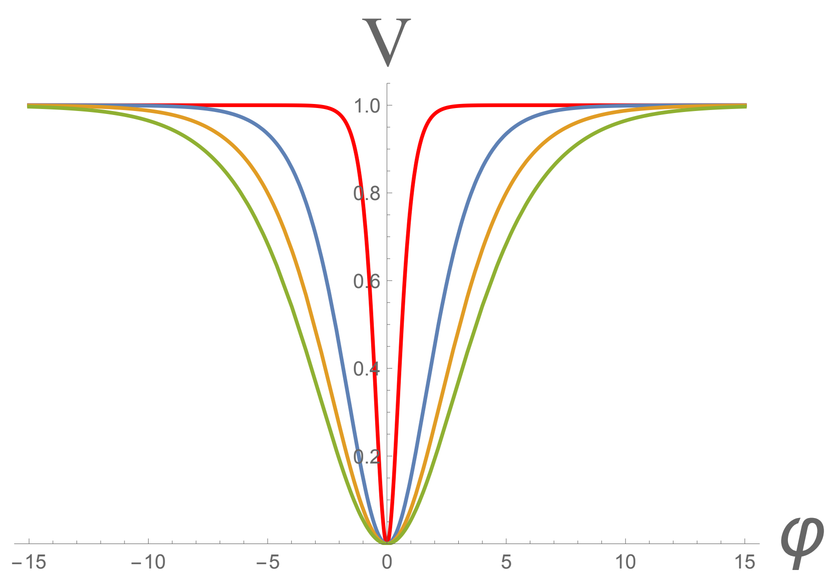
GL model as an α-attractor

Kallosh, AL 2015

$$K = -3\log\left(1 - Z\bar{Z} + \frac{\alpha - 1}{2}\frac{(Z-\bar{Z})^2}{1-Z\bar{Z}}\right)$$

$$W = \frac{\mu}{9} Z^2 (1 - Z^2)$$

GL model is the single-field model with α =1/9.



SUSY breaking and uplift in GL model

Add to GL model a linear term containing a nilpotent field S, and we get a simple **inflationary** model describing **SUSY breaking** and the **cosmological constant**:

$$W = \frac{\mu}{9} Z^2 (1 - Z^2) + M(S + 1/b)$$

$$m_{3/2} = M/b \qquad\qquad V_0 = M^2(1 - 3/b^2)$$

Note that the cosmological constant appears only when SUSY is broken. The term M(S+1/b) is similar to Polonyi superpotential. However, the field S is nilpotent, it vanishes, so there is no cosmological moduli associated with the Polonyi field.

Kallosh, AL 2015, Roest, Scalisi 2015, AL 2015, Scalisi 2015

α–attractors with SUSY breaking and a cosmological constant

$$W = \Big(S + \frac{1-Z^2}{b}\Big)(\sqrt{3}\alpha\, m^2\, Z^2 + M)$$

S – nilpotent superfield (no scalar component)

m - inflaton mass scale

M - SUSY breaking mass scale

$$\Lambda = M^2(1 - \frac{3}{b^2})$$

For $b = \sqrt{3}$ one has $\Lambda = 0$. Changing b gives any desirable value of the cosmological constant.

No need for a Polonyi field, so no cosmological light moduli problem.

Kallosh, AL 1502.07733, Carrasco, Kallosh, AL 1506.01708

Conclusions:

Because of the stimulating pressure from observations, we found a new classes of theories with very interesting properties: cosmological attractors. Their predictions are stable with respect to strong modifications of the inflaton potential, and they can describe in a very economical way not only inflation but also dark energy and SUSY breaking.

Conclusions:

For 30 years, one of our main goals was to use observations to reconstruct inflationary potential. However, in this new class of theories, cosmological predictions depend mostly not on the potential, but on geometry of the moduli space.

Thus investigation of geometry of space-time may provide information about geometry of the moduli space.